Stability Results

The cycle length variability, determined from the RV electrograms in early spontaneous VT, decreased as VT progressed. Figure 7 shows the mean values of the beat-by-beat changes in cycle length beginning with the first short cycle length of the sustained VTs. The first 3 beats of spontaneous VT exhibited much more instability than subsequent beats although stabilization appears to continue for many beats.

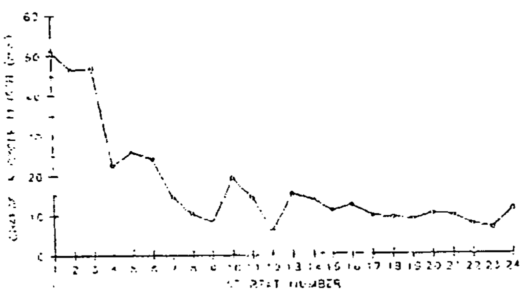

Figure 7. Early VT Cycle Length Instability.

The 22 episodes of spontaneous sustained VT were repeatedly applied to the VT detection algorithm for STABILITY programmed throughout the range 10 ms to 100 ms. Starting with the first VT beat, the VT detection delay was due to resetting of the VT counter by stability. The detection delay for the first 25 beats of VT was plotted versus the STABILITY parameter in Figure 8. For STABILITY less than 50 ms, the detection delay was inversely proportional to STABILITY.

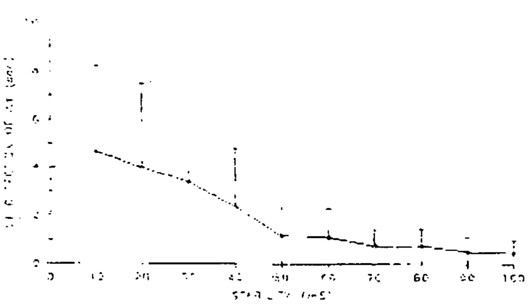

Figure 8. VT Detection Delay Due to Stability.

For 22 VT episodes and 9 atrial fibrillation episodes, the number of stability resets was determined as a function of the STABILITY parameter in the range from 10 ms to 100 ms. The results were plotted in Figure 9 for episodes with 25 beats of stabilized VT and for 25 beats of atrial fibrillation (AF) data. STABILITY should reject AF by frequently resetting the VT counter without preventing or significantly delaying detection of VT. As the STABILITY parameter increased, the number of stability resets decreased for both VT and AF. Since Figures 7 and 8 show that most stability resets occur early in the VT, a STABILITY value of 50 or 60 ms may be optimal.

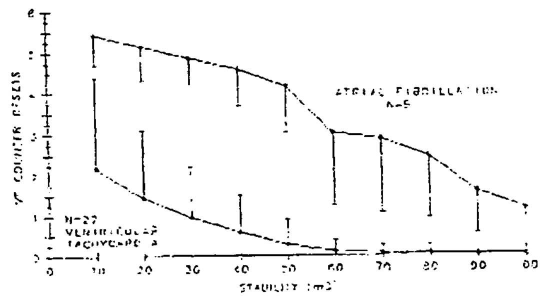

Figure 9. Stability For AF vs. VT.

Discussion

The major disadvantage of rate detection for VT and VF is the lack of specificity. Simple onset and stability algorithms did not perform well on these spontaneous ventricular arrhythmias. The more complex onset and stability algorithms described in this paper performed well on our limited database of 22 spontaneous ventricular arrhythmias. True evaluation must await clinical study and collection of additional databases. The presumed specificity of onset and stability has not been evaluated with sinus tachycardia or an adequate variety of supraventricular arrhythmias. Very high sensitivity for PCD devices is essential, even at the expense of specificity because the consequences of false negative VT and VF detection is so grave.

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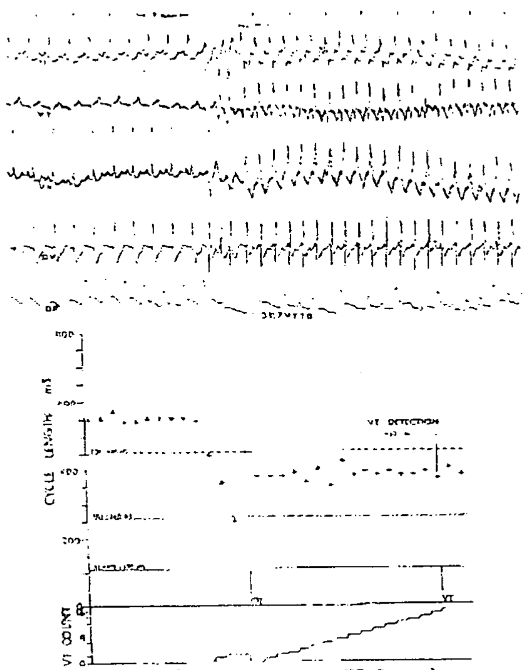

Figure 3. Spontaneous VT Example.

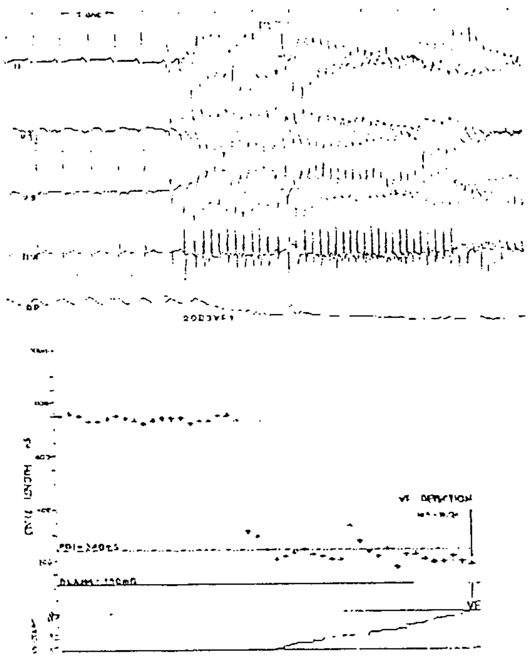

Figure 4. Spontaneous VF Example.

beat. For the 7th, 12th, 13th and 16th cycle lengths the VF counter did not increase because the cycle lengths were not less than the FDI. On the 25th beat, VF was detected because 18 of the previous 24 beats had cycle lengths less than FDI.

Onset Results

All 22 episodes of spontaneous sustained VT were repeatedly applied to the VT detection algorithm for ONSET values ranging from 6 to 97%. Onset detection for every VT episode was a simple threshold as a function of onset percentage. Figure 5 shows the cumulative distribution of onset thresholds for the 22 episodes as a function of onset percentage. Onset was always detected for all episodes when ONSET $\geq$ 81%. Detection never occurred for onset percentages less than 37%. In 9 of the 22 episodes the beat where onset was detected shifted earlier by one beat at higher onset percentages and one episode shifted by 2 beats. As the onset percentage increased, the spontaneous sustained episode met the onset before PVCs were detected. In 11 episodes 2 - 4 PVCs set and reset the onset at higher onset percentages. Slower VTs might be expected to require higher onset percentages for detection because of smaller cycle length changes. Figure 6 is a plot of the onset percentage for detection versus the VT cycle length. Considerable scatter was seen ($r = 0.48$).

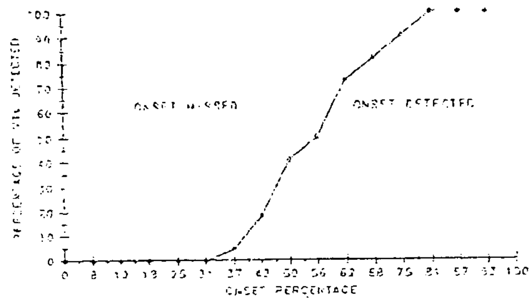

Figure 5. Cumulative Distribution of Onset.

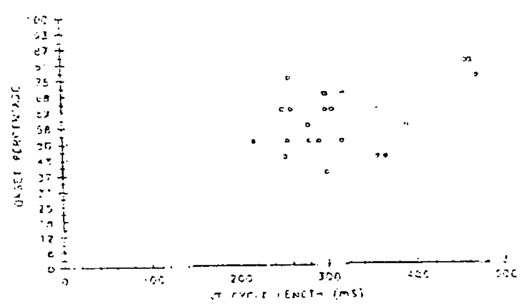

Figure 6. Onset vs. VT Cycle Length.

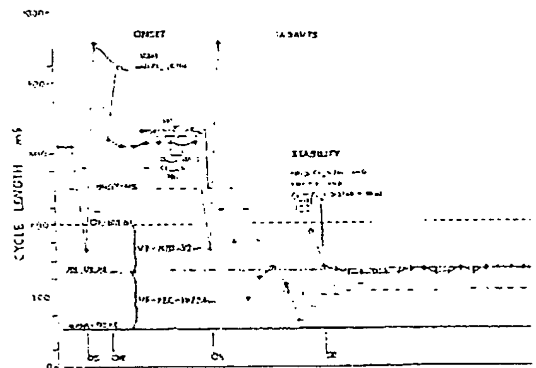

Figure 2. VT-VF Detection Algorithm.

tion Interval (FDI) are the most important parameters. The TDI must always be greater than the FDI. Note that blanking following ventricular sensing is 120 ms. Basic VT detection requires that a programmable consecutive Number of Intervals for Detection (NID) occur between TDI and FDI. Whenever even one interval is longer than or equal to TDI, the VT counter resets to zero. Any interval less than FDI does not affect the VT counter.

Since sinus tachycardia rates overlap with slow VT rates, an optional ONSET condition requires a sudden change in rate at the beginning of the tachycardia. To set the ONSET, the current cycle length CL_n must be less than the average of the four previous cycle lengths, times the programmable ONSET percentage (56% - 97%). In Figure 2, note that ONSET was set (OS) on the third and the thirteenth beats. An additional requirement for setting ONSET is that one or both of the N-2 and N-3 cycle lengths must be greater than or equal to TDI. This prevents a PVC in sinus tachycardia with cycle length less than TDI from setting ONSET. The ONSET condition is tested on every beat since some paroxysmal onsets for VT begin with a cycle length that is not quite below TDI although subsequent beats fall below TDI. The ONSET condition is reset when two consecutive cycle lengths are greater than TDI. Note that ONSET was reset (OR) on the fifth beat in Figure 2. If this occurs during VT when TDI is too close to the cycle length of the VT, then VT detection can be missed regardless of the duration of the tachycardia. The ONSET condition applies only to the first detection of VT in a VT episode.

The optional STABILITY criterion for VT detection is intended to add specificity by rejecting atrial fibrillation rhythms with irregular cycle lengths and rejecting polymorphic VT with irregular cycle lengths. The VT therapies are not effective for these rhythms. The STABILITY criterion is tested only when the current cycle length CL_n is between TDI and FDI and the VT counter is greater than three. The VT counter is reset to zero if any one of the three previous cycle lengths differs in absolute value from the current cycle length, CL_n, by more than the programmable STABILITY parameter (10 - 150 ms). In Figure 2 this stability reset (SR) of the VT counter occurred at the beat indicated by the arrows. Resetting the VT counter at this time appears appropriate because the VT was polymorphic with unstable cycle lengths. A stability reset (SR) did not occur on the previous beat because the VT counter had not reached four.

Detection of ventricular fibrillation (VF) depends only on rate; however, the Fibrillation Event Counter (FEC) does not require consecutive intervals less than FDI to achieve detection. VF detection occurs when three-fourths of the intervals in a programmable series of consecutive beats have cycle lengths less than the FDI. For example, in Figure 2, if any 18 of the last 24 intervals are less than the FDI, then VF detection occurs. During VF the amplitude of electrograms may be low and VF can still be detected even if some of the depolarizations with short cycle lengths are not detected. If acceleration of VT occurs, VF detection takes precedence over VT detection.

Detection of VT or VF initiates a VT or VF episode, respectively. Following the first VT or VF therapy, detection resumes and, if 8 consecutive intervals are greater than or equal to the TDI or FDI respectively, then the episode is terminated. If the respective VT or VF is detected again following the first therapy, then the second progressive therapy is delivered. Up to 4 progressive VT therapies and 4 progressive VF therapies can be programmed. Following a VT therapy, both VT and VF detection are active so that accelerated rhythms can be detected. VT detection is disabled for 64 beats after VF therapies. If all 4 of the respective VT or VF therapies fail to terminate the arrhythmia and detection occurs again, then the respective detection algorithm is disabled until episode termination is detected or detection is reenabled by programming.

Examples

Ventricular Tachycardia

In Figure 3, the three surface leads and the RV electrogram show that the early VT morphology was different from the sustained VT morphology. The detection cycle length graph shows that the VT cycle lengths for the first four beats of the VT were very unstable. The first two VT beats were counted because the cycle lengths were in the VT range. The third beat cycle length was less than FDI, so the VT count was unchanged. The fourth beat cycle length was equal to the TDI so the VT counter was reset (CR). The fifth and subsequent beats all incremented the VT counter until VT detection occurred when the VT count reached NID=16.

Ventricular Fibrillation

Spontaneous ventricular fibrillation as shown in Figure 4 began with a sinus fusion beat followed by polymorphic VT that progressed rapidly to VF. On the detection cycle length graph the first three cycle lengths of the VF were not less than the FDI so the VF counter began with the fourth

ONSET AND STABILITY FOR VENTRICULAR TACHYARRHYTHMIA DETECTION
IN AN IMPLANTABLE PACER-CARDIOVERTER-DEFIBRILLATOR

Walter H. Olson, Gust H. Bardy*, Rahul Mehra, John G. Keimel,
Kenneth F. Huberty, Carolyn Almquist, Randy M. Biallas

Pacing Research, Medtronic, Inc., Minneapolis, MN and
*Division of Cardiology, University of Washington, Harborview Medical Center, Seattle, WA

Abstract

A tachyarrhythmia detection algorithm for an implantable Pacer-Cardioverter-Defibrillator (PCD) is described and tested with a spontaneous ventricular arrhythmia database. Ventricular tachycardia (VT) detection can use sustained rapid rate, paroxysmal onset and rate stability. A VT episode begins with VT detection leading to progressive pacing and cardioversion therapies until VT termination is detected. Simultaneous ventricular fibrillation (VF) detection for automatic defibrillation uses a higher rate threshold that can tolerate partial loss of sensing. This algorithm was developed using a new database of spontaneous VT and VF intracardiac electrograms recorded from sudden death survivors in an intensive care unit. Results show that optional onset and stability parameters add specificity to simple VT rate detection without reducing sensitivity.

Introduction

Reliable automatic detection of VT and VF for a PCD with limited analytic capacity requires simple parameters with high sensitivity and specificity. High rate is used by all tachyarrhythmia pacemakers[1] and the AICD defibrillator.[2] One anti-SVT pacemaker[1] also uses simple onset and stability criteria to add specificity. An algorithm for processing atrial and ventricular timing and the response to atrial extrastimuli has been proposed.[3] For VF detection, the probability density function,[2] intracardiac impedance[2] and intracardiac pressure[2] can add specificity to high rate detection.

Spontaneous Arrhythmia Database

Forty survivors of out-of-hospital ventricular fibrillation were studied at the University of Washington, Harborview Medical Center Coronary Care Unit, from December 1984 to February 1986. Continuous analog tape recordings of surface ECGs (II, V1, V5), bipolar right ventricular electrograms, intracardiac impedance, esophageal electrograms and arterial blood pressure were made for 1 to 5 days after admission depending on clinical circumstances using the equipment in Figure 1.

Right ventricular electrograms were recorded with Medtronic 10240 tripolar temporary leads between

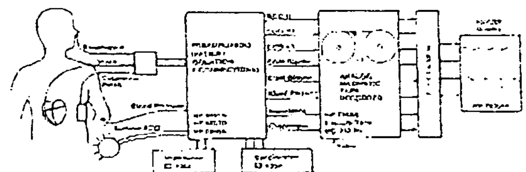

Figure 1. Database Acquisition System

an 8 mm^2 ring tip and 125 mm^2 distal ring electrode separated 5 mm from the tip. Esophageal atrial electrograms were recorded using a Medtronic 6992 lead whenever possible to document ventriculoatrial dissociation during ventricular tachycardia. All the analog tapes were logged and scanned for arrhythmias and other clinical events. Twenty-two episodes of spontaneous sustained ventricular tachycardia and ventricular fibrillation were selected from the 10 patients with sustained (30 sec or shock) ventricular arrhythmias. No more than 3 episodes per patient were utilized. Nine episodes of spontaneous supraventricular tachycardia and atrial fibrillation from three patients were also analyzed. Since surface ECGs at the beginning of spontaneous ventricular arrhythmias exhibit simultaneous changes in cycle length and QRS morphology, accurate cycle length measurements from surface ECGs are difficult. Intracardiac electrograms from bipolar electrodes change morphology less than surface ECGs and maintain high slew rates because of the near-field relation to the myocardium. Therefore, the bipolar electrogram was used to determine cycle lengths with a variable threshold pacemaker sense amplifier. Computer analysis of detected cycle lengths with 10 msec resolution was done on a DEC MicroVax II with a program that emulated in every detail the software in the Medtronic 7215 Pacer-Cardioverter-Defibrillator (PCD).

VT-VF Detection Algorithm

The detection algorithm independently detects ventricular tachycardia for pacing and cardioversion therapies and ventricular fibrillation for defibrillation therapies. The major parameters and conditions are illustrated on an example of spontaneous ventricular tachycardia in Figure 2.

Two rate limits, one for VT detection called the Tachycardia Detection Interval (TDI) and another for VF detection called the Fibrillation Detec-

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